

Solar Cycle Variations and Equatorial Oscillations: Modeling Study

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Abstract. Solar cycle activity effects (SCAE) in the lower and middle atmosphere, reported in several studies, are difficult to explain on the basis of the small changes in solar radiation that accompany the 11-year cycle. It is therefore natural to speculate that dynamical processes may come into play to produce a leverage. Such a leverage may be provided by the Quasi-Biennial Oscillation (QBO) in the zonal circulation of the stratosphere, which has been linked to solar activity variations [e.g., Labitzke (1982, 1987) and Labitzke and van Loon (1988, 1992)]. Driven primarily by wave mean flow interaction, the QBO period and its amplitude are variable but are also strongly influenced by the seasonal cycle in the solar radiation. This influence extends to low altitudes referred to as “downward control”. Relatively small changes in solar radiative forcing can produce small changes in the period and phase of the QBO, but this in turn can produce measurable differences in the wind field. Thus, the QBO may be an amplifier of solar activity variations and a natural conduit of these variations to lower altitudes. To test this hypothesis, we conducted experiments with a 2D version of our Numerical Spectral Model that incorporates Hines’ Doppler Spread Parameterization for small-scale gravity waves (GW). Solar cycle radiance variations (SCRV) are accounted for by changing the radiative heating rate on a logarithmic scale from 0.1% at the surface to 1% at 50 km to 10% at 100 km. With and without SCR, but with the same GW flux, we then conduct numerical experiments to evaluate the magnitude of the SCAE in the zonal circulation. The numerical results indicate that, under certain conditions, the SCAE is significant and can extend to lower altitudes where the SCR is inconsequential. At 20-km the differences in the modeled wind velocities are as large as 5 m/s. For a modeled QBO period of 30 months, we find that the seasonal cycle in the solar forcing [through the Semi-annual Oscillation (SAO)] acts as a strong pacemaker to lockup the phase and period of the QBO. The SCAE then shows up primarily as a distinct but relatively weak amplitude modulation. But with the QBO period between 30 and 34 (or < 30 , presumably) months, the seasonal phase lock is weak. Solar flux radiance variations in the seasonal cycle then cause variations in the QBO period and phase that amplify the SCAE to produce relatively large variations in the wind field. These variations also extend to mid latitudes.

1. Introduction

Following a study by Holton and Tan (1980) that revealed an influence of the phase of the Quasi-Biennial Oscillation (QBO) on the dynamics of the stratosphere, Labitzke (1982, 1987) and Labitzke and van Loon (1988, 1992) discovered that the temperatures at northern polar latitudes in winter are positively and negatively correlated with the solar cycle activity when the QBO was in its negative and positive phase respectively. At mid-latitudes they observed opposite correlations. Naito and Hirota (1997) later confirmed these findings. In the northern stratosphere and for the period between 1964 and 1994, Dunkerton and Baldwin (1992) and Baldwin and Dunkerton (1998) found evidence of a quasi decadal oscillation that correlated with the Quasi Biennial Oscillation (QBO) and solar cycle.

A GCM modeling study by Balachandran and Rind (1995) found general agreement with the above observations. They also found that their model produced a significant solar activity effect in the troposphere. Balachandran et al. (1999) later extended this study and found, in agreement with observations, a significant increase of geopotential heights during solar maximum that is correlated with the phase of the QBO. They attributed their results to the changing vertical gradients of temperature and zonal winds that are produced by the changing solar radiation. These geopotential height changes then alter the propagation conditions for planetary waves, which in turn affected the circulation at lower altitudes.

From the above results it is not, however, readily apparent what role the QBO is actually playing in the solar activity effects that have been reported. The QBO and its phase in particular, may act as a catalyst to change the propagation conditions for waves and bring about the observed solar cycle activity connection. To complicate this picture, the QBO itself may also be affected directly by solar activity. And this is the avenue we are examining in the present paper.

2. QBO, Downward Control, and Period Modulation

Unlike the annual oscillation (AO) and semi-annual oscillation (SAO) in the atmosphere, whose periods of 12 and 6 months respectively are controlled by the seasonal variations of solar radiation, the QBO with periods between 20 and 32 months is controlled primarily by dynamical

processes. Lindzen and Holton (1968) first showed that, under the influence of the seasonal cycle, wave mean flow interactions can generate the QBO in the zonal circulation at low latitudes. Holton and Lindzen (1972) concluded that the influence of the seasonal cycle does play a role but is not essential to generate this kind of oscillation.

Owing to its generation mechanism, the QBO could therefore be a natural conduit for transferring the effect solar cycle radiance variations (SCRV) to lower altitudes. Two factors are of particular importance.

First, waves can efficiently generate the QBO at equatorial latitudes because, with the Coriolis force vanishing, the meridional circulation is not important in the redistribution of equatorial wave momentum. Thus, the equatorial wave momentum that drives the QBO remains near the equator and can couple back downward to lower altitudes by momentum transfer (diffusion). This redistribution of momentum with altitude is referred to as wave driven “downward control” and to a lesser degree can occur also outside the tropics wherever wave mean flow interactions are important.

Second, the QBO is influenced by the seasonal variation in the solar radiative forcing (Lindzen and Holton, 1968; Holton and Lindzen, 1972). This was shown explicitly in computer experiments (Mayr et al., 1998), reproduced in Figure 1, that generated equatorial oscillations with the seasonal cycle of solar heating (a) and for comparison with constant solar heating at perpetual equinox (b). The seasonal cycle causes in the QBO a significant increase in amplitude from 3 to 7 m/s at 30 km and increases its period from about 17 to 21 months. The computed amplitude of the dominant oscillation at higher altitudes also increases but its period decreases from 8 to 6 months to produce the SAO that is phase locked to the seasonal cycle with the Sun crossing the equator twice a year.

In the equatorial QBO momentum deposited by upward propagating waves is transferred to lower altitudes through diffusion. To some extent, this downward control is modulated by the seasonal variations in the solar heating of the mesosphere, where solar influences play a significant role. Through the seasonal cycle, long-term solar cycle radiance variations (SCRV) then influence the amplitude and period of the QBO. By changing the period of the QBO in particular, the SCRV thus can exert leverage on the SCAE at lower altitudes through downward control as suggested in this paper.

Based on the analyses we have carried out, two other processes influence and involve the QBO. One is synchronization of the QBO by the seasonal cycle of solar forcing (Mayr et al., 2000). The other one involves the QBO to produce beat periods between 5 and 10 years through GW node filtering that causes interaction with the seasonal cycles (Mayr et al., 2001). As shown in this paper, these processes can also come into play to influence the SCAE and thus further complicate our understanding.

In the following, we shall briefly describe our model and the gravity wave parameterization that is employed to drive the QBO. We shall then present the results from computer experiments for QBOs with periods of about 30 and 33 months, for which the SCAEs are vastly different owing in part to the importance of period modulation relative to amplitude modulation.

3. Model

The simulations presented here use a 2D version of the Numerical Spectral Model (NSM) whose numerical design was discussed by Chan et al. (1994). The 2D version of the model is time dependent and non-linear, but is simplified in that perturbation theory is applied to compute the wind fields and the temperature and density perturbations about a globally averaged background atmosphere. With the typical temperature perturbations being less than 10%, the radiative energy loss is formulated in terms of Newtonian cooling, which reduces the computational effort significantly. The model atmosphere extends from the Earth's surface to the top of the thermosphere at 400 km, but in the present study the upper boundary is at 240 km, which is well above the region of primary interest. In 2D, the zonally averaged component (zonal wavenumber $m = 0$) is driven by solar UV radiation absorbed in the stratosphere and mesosphere (Strobel, 1978) and by EUV radiation absorbed in the thermosphere.

To simulate SCRV perturbations to the atmosphere we adjust the models internal heating rates using the simple scheme illustrated in Figure 2. We assume that the solar radiative heating sources vary with solar cycle on a logarithmic scale by 0.1% at the surface, 1% at 50 km and 10% at 100 km and above. The variations below 30 km, however, are irrelevant since the model only accounts for solar heating due to UV and EUV radiation in the stratosphere, mesosphere and thermosphere.

Above 100 km, observed solar radiance variations are much larger but are assumed to have negligible influence on the atmospheric perturbations in the middle atmosphere.

Planetary-scale Kelvin and Rossby-gravity waves were originally thought to be responsible for the QBO (e.g. Lindzen and Holton 1968). Recent satellite measurements and modeling studies, however, show that additional momentum sources are required. Small-scale gravity waves are now also believed to be important in generating the QBO (Mengel et al., 1995; Dunkerton, 1997; Mayr et al., 1997).

Since gravity waves (GW) cannot be resolved in global-scale models, their interaction with the background wind field needs to be parameterized. Lindzen (1981) first developed such a scheme. In the NSM we use have used the Doppler spread parameterization developed by Hines (1997a, b). This parameterization considers a spectrum of gravity-waves and accounts for the non-linear interactions between the waves (treated like background winds) that in turn affects significantly the wave-mean flow interaction. In addition to the wave momentum source the parameterization also provides the vertical eddy diffusivity due to wave driven turbulence. The wave momentum flux from the Hines parameterization is proportional to $\sigma_h^3 k_\star$, where σ_h is the GW horizontal wind variability (2 to 3 m/s at 20 km) and k_\star is the characteristic horizontal wave number $(100 \text{ km})^{-1} \leq k_\star (10 \text{ km})^{-1}$. For simplicity, these parameters are taken to be globally uniform and independent of season.

4. Solar Activity Case Studies

The purpose of this study is to elucidate possible dynamical mechanisms that might contribute to the solar cycle activity effects (SCAE) observed in the lower atmosphere. We ask whether the equatorial oscillations, and in particular the QBO, could bring about the SCAE through downward control. Addressing this question, two case studies are presented. The first describes a hypothetical QBO with an average period of 30 months that is phase locked with the seasonal variations. The second study deals with a hypothetical case where the average QBO period is about 33 months, near the upper end of the observations. In the first case, the SCAE is relatively small and appears primarily as an amplitude modulation of the QBO. In the second case, the SCAE is much larger and is accompanied by phase variations of the QBO that are more difficult to understand.

4.1 Case Study 1 with 30-months QBO

With a period of 30 months, the phase condition is optimally satisfied for the QBO to be synchronized by the semiannual variations (e.g., Mayr et al., 2000). Under this condition, the seasonal cycle acts as a strong pacemaker for the QBO. To produce the 30-months QBO, we chose the GW parameters to be $k_* = (60 \text{ km})^{-1}$ and $\sigma_{hi} = 2 \text{ m/s}$ at 20 km. The GWs are assumed to be generated isotropically at the surface and are taken to be independent of latitude and season. In an effort to reduce the feedback from the seasonal variations, to produce a more stable QBO period, the solar heating rate was reduced by about 20% so that the zonal winds at mid latitudes (eastward in winter and westward in summer) are only around 40 m/s.

Allowing for sufficient spin-up time, the numerical experiments were performed by running the model for 30 years. First, we present the results obtained without imposing any SCRV. The computed monthly mean zonal winds at 4° and 40° in the northern hemisphere are shown in Figure 3. Two related features are of particular interest. Firstly, the QBO at 4° latitude is modulated with a beat period of 5 years (Mayr et al., 2000), which is generated through GW node filtering by interaction with the annual oscillation (AO). Secondly, at low latitudes, the signature of the AO induced beat period extends down to 10 km, while the AO itself is confined to altitudes above 30 km at mid latitudes where it dominates.

These features are delineated in more detail in the spectrum of the zonal winds at 4° latitude that is shown in Figure 4 for time span of 30 years. The spectrum is plotted in terms of the harmonics, h , with the associated periods determined by $30/h$ (in years). The spectrum is presented separately for the hemispherically symmetric (a) and asymmetric (b) components; and the dominant lines for the symmetric QBO and SAO and asymmetric AO are identified. Also identified is the asymmetric 5-year beat period, which is produced by the symmetric QBO interacting with the asymmetric AO. While the 5-year beat period is weak, it is more pronounced in the side-lobes (harmonics) that are identified at harmonics $h = 6$ and 18 for the QBO, at 24 and 36 for the AO, and at 54 and 66 for the SAO. Unlike the 5-year beat period, which is generated above 40 km, the resulting side-lobes extend to lower altitudes with much larger amplitudes. This again illustrates the importance of downward control at low latitudes, which effectively modulates not only the QBO but significantly the AO and SAO as well. All the other features in the model spectrum can be explained by the QBO interacting with the seasonal cycles, such as the oscillations at $h = 48$ and 72 resulting from SAO-QBO coupling.

Except for the AO and SAO, all the spectral lines in the simulation are related to the QBO, either directly or indirectly.

When we run the model with the solar activity variations illustrated in Figure 2, the resulting zonal wind field at low latitudes is different from that shown in Figure 3a. The resulting changes, however, are not large enough to identify an obvious solar activity signature. We therefore take the approach of directly examining the difference fields instead. One of the quantities to compare is the period of the QBO, which is determined from the time spans the winds change direction. This QBO period is presented for model runs with and without solar activity variations in Figure 5 for 20-km altitude at 4° latitude. It shows that the QBO period varies around 30 months, and the variations clearly reveal the 5-year beat period that is generated by the interaction with the AO. The differences between the solutions with and without solar activity, however, are slight. As pointed out earlier, in this particular case, the AO acts as a strong pacemaker to lock the period of the QBO – which is by no means typical as the second case study will show where the variations are less regular, and the solar activity related differences between the QBO periods are much larger.

In Figure 6a we show for 4° latitude the yearly average of the differences between the zonal winds computed without and with solar activity variations. The pattern seen here clearly reveals the 10-year periodicity imposed by the solar activity cycle, but the signal is not as clean as one would have liked to see. The tongs that extend down to lower altitudes around the year 5, are also there at around 15, but they are split up around the year 25. At altitudes above 70 km, the zonal wind differences tend to be out of phase with those below, and again show the resemblance of the imposed 10-year solar activity cycle. Considering that the assumed relative solar activity variations vary from 1% to 10% from 50 to 100 km respectively, the resulting zonal wind differences of about 10 m/s at around 60 km are large. But the effect does not grow proportionally with altitude, which suggests that the amplification is tied to the stratospheric QBO and that the signatures in the upper mesosphere are produced by the filtering of upward propagating GWs.

To gain further insight we also ran the model also with a factor-of-three increase in the solar activity variations relative to those shown in Figure 2. For the QBO period, the differences are slightly larger compared to Figure 5, but the differences are not large enough to be significant. The differences in the zonal winds, shown in Figure 6b, however are significant. Compared with

Figure 6a, the phases of the zonal wind differences (i.e., patches of positive and negative values) are in general agreement, as one should expect from the identical phasing of the adopted solar cycle variations. The wind differences are also larger during the first 10-year cycle, and they extend to lower altitudes. During the second cycle, however, the wind differences are smaller and they are confined to altitudes above 50 km. Then during the third cycle, there is again a tendency for the perturbations to increase in magnitude and to extend to lower altitudes. Overall, however, the factor of three increase of the SCRV does not produce a corresponding increase in the difference field. This reveals one of the difficulties in our understanding of the underlying processes that are inherently non-linear.

The picture is somewhat clearer, when the zonal wind differences are presented in spectral notation as shown in Figure 7 for the symmetric components (the contour interval is 0.5 m/s, and the minimum value is chosen to be 1 m/s). For both solar activity levels, the 10-year harmonic stands out at $h = 3$, along with the side-lobes at $h = 9$ and 15 that describe the solar activity modulation of the QBO. With increased SCAV, the amplitudes are also noticeably enhanced. Other notable differences are seen in the harmonics $h = 5$ and 7 that sharpen with enhanced activity. With 3x SCAV, prominent features appear also at $h = 33$ and 39, which can be related to one of the side-lobes at $h = 36$ shown in Figure 4 that in turn is produced by the modulation of the AO with the 5-year beat period. And the features at $h = 69$ and 76 can be related to one of the side-lobes at 72 shown in Figure 4, which is produced by the modulation of the SAO with the QBO. Most of the features in the difference spectrum that appear only in the solution with 3x SCAV thus can be traced to complicated dynamical interactions involving the AO and SAO – and this may in part explain the above discussed differences between Figures 6a and 6b.

From the spectra shown in Figure 7, we can synthesize the dominant lines to create a filtered picture of the difference fields. These are shown in Figures 8a and 8b for the two levels of SCRV. For comparison, we employ in both cases the same prominent harmonics: $h = 3$ for the 10-year solar cycle, and $h = 9$ and for the 10-year side-lobes of the QBO. These synthesized difference fields thus describe only the filtered first-order SCAE. Not surprisingly, the features that appeared in Figure 6a also appears again in Figure 8a, since the chosen harmonics essentially describe the bulk of the difference field. This is not true for Figures 6b and 8b, since there the adopted spectral lines only describe a subset of the computed difference field. For the

filtered difference field, the 10-year amplitude modulation increases significantly with increased SCRV, and the effect extends to lower altitudes.

For completeness, we present in Figure 9 the computed difference fields at 40° latitude. The zonal wind fields at these latitudes do not show any sign of the 10-year activity cycle. For both levels of activity, the magnitudes of the wind differences are small, and the variations do not indicate any trends. The spectral representation (not shown) confirms this conclusion.

In summary, we have seen from this case that the solar activity effect is confined to low latitudes where it appears to show up as an amplitude modulation of the QBO. In this particular instance, the QBO is being synchronized by the seasonal cycle so that its period and phase become tightly locked. The situation is thus unusual for this 30-months QBO, but it provides a valuable reference for the next case study where the results are more complex and difficult to understand.

4.2 Case Study 2 with 33-months QBO

For the hypothetical 33-months QBO, the model was run for 50 years. The GW parameters were taken to be $k_* = (65 \text{ km})^{-1}$ and $\sigma_h = 3 \text{ m/s}$ at 20 km to produce a factor of 2 larger momentum flux, but the adopted eddy diffusion rate was also almost a factor of 2 larger to assure numerical stability. Additionally the numerical experiments were performed using a shorter integration time step of less than 5 minutes. Standard solar heating rates were employed to produce zonal winds of about 70 m/s in the winter hemisphere at mid latitudes. This QBO was discussed by Mayr et al. (2001) as an example to illustrate how it can generate a quasi-decadal oscillation in the form of a beat period resulting from an interaction with the SAO through GW filtering.

In Figure 10a, we present at 4° N the computed zonal winds averaged over a year. The period of the QBO is on average 33.5 months. Repeatable features indicate a modulation with a period around 10 years, but the pattern is not as clean as that for the 5-year beat period seen in Figure 3. As Figure 10b shows, the amplitude modulation of the zonal winds are large at 40° N . During the first cycle, the modulation period is close to 11 years, but for the second cycle it is closer to 9 years. Apparently, the beat period is fluctuating around 10 years, and this adds a potential complication when solar activity variations with such a duration are employed.

Analogous to Figure 5, we present with Figure 11 the variations of the periodicity of the zonal winds at 20 km computed without and with solar activity variations. Because of the

conflicting 10-year beat period that comes into play in this case, the model was also run with hypothetical solar cycle periods of 8 years (b) and 13 years (not shown). In contrast to Figure 5 for the 30-months QBO that is phase locked to the seasonal cycle, the periodicity in Figure 11 is highly variable without revealing any discernable patterns. The same is true for the solutions with solar activity variations, which differ also significantly for the two different periodicities chosen.

That the QBO period in this case, and in general, is variable is not surprising. Waves propagating up are filtered by the QBO and as a result influence the AO and SAO, as the spectral lines in Figure 4 illustrate that tie these components together. On the other hand, we have also seen that the AO and SAO, influenced by the QBO, in turn influence the QBO even to the extent to act as a strong pacemaker to produce a phase lock in the previous case study (e.g., Figure 5). The two interactions, transferring momentum both upwards and downwards, are inherently non-linear and are strongly non-linear due to the importance of the feedback process. This introduces into the dynamical system a significant quasi-chaotic component that is difficult to unravel.

The effect is dramatic when the model in this case is run to account for SCRV. With the 10-year activity cycle, the phase of the QBO gradually changes so that after about 7 years the polarity (sign) of the oscillation changes. The oscillation then continues in this phase for the remaining 40 years of the numerical experiment. This is shown in Figure 12a for the difference field, with contour intervals of 10 m/s, reaching magnitudes twice as large as those shown in Figure 10a. Apparently, the phase variations introduced by the 10-year solar activity variation drives the atmosphere into another configuration that is commensurate with, and becomes locked to, the natural beat period of 10-years. Apparently this is caused by the coincidence of the two periodicities.

As mentioned earlier, to avoid this coincidence of the periods of solar activity and beat period, the model was also run with a hypothetical 8-year activity cycle. The result for the difference field is presented in Figure 12b with contour intervals of 5 m/s. In this case, the oscillation at lower altitudes below 30 km also builds up but much later after more than 25 years, and the velocities do not come close to those generated in Figure 12a. In contrast to the previous case, the activity cycle is not synchronized with the beat period. On the other hand, the results show that the difference field is not dominated by a period of 8 years but one that is closer to 10 years, suggesting that the beat period continues to play a role.

To provide more insight, we present in Figure 13 for 4° N the spectra computed from a 40 year time span of the difference fields (with 1 m/s contour intervals starting at 3 m/s). Along with the 10-year signal of the activity cycle and its second harmonic at $h = 8$, the figure shows the large QBO amplitude that results from the phase reversal discussed above. The other prominent features in the spectrum are associated with the AO and SAO, although these are not present in the difference field as expected. The asymmetric side-lobes $h = 36$ and 44 are caused by a 10-year modulation of the AO. The features at $h = 26$ and 54 result from the modulation of the AO by the QBO. The symmetric harmonics at $h = 76$ and 84 are related to the SAO modulation by the 10-year activity cycle, and the features at $h = 66$ and 94 are related to the QBO modulation. Of the remaining spectral features, we recognize the symmetric harmonics close to $h = 10$ and 18 that reveal the 10-year modulation of the QBO, and the signal at $h = 43$ represents the third harmonic of the QBO that is a characteristic of the non-linear wave mean flow interaction involved in generating this oscillation. Of considerable interest are also the symmetric features at $h = 62$ and 98 , which appear to be the side-lobes of the QBO associated with the 10-year activity cycle that in turn modulate the SAO. And the same pattern is apparent in the asymmetric harmonics at $h = 22$ and 58 that reveal the corresponding interactions with the AO. These cascades of energy reveal the complex nature of the interactions involved.

For the 8-year activity cycle presented in Figure 13b, the spectrum contains many of the same features discussed above. The QBO modulation signatures are present in this simulation but are much weaker than those seen in Figure 12. The signal of the activity cycle is seen in the 10-year harmonic at $h = 4$ and its second harmonic at 8 . These are accompanied by a strong feature at $h = 6$ that corresponds to a period of about 6.7 years, which appears to indicate a shift towards 8 years. We note the side-lobes at $h = 10$ and 18 that show the 10-year modulation of the QBO. The SCRV related harmonics at $h = 4, 6$, and 8 create additional side-lobes for the AO and SAO. Of interest again are the features at $h = 22$ and 58 for the AO and those at $h = 62$ and 82 for the SAO, which can be related to the 10-year modulation of the QBO as seen also in Figure 13a.

Unlike in the first case study for the phase locked QBO, the SCAE in the difference field now extends to higher latitudes as shown in Figure 14. Distinct SCAE signatures are seen here, with differences in the wind field of ± 10 m/s that reveal periodicities around 10 years. The pattern though is less pronounced for the 8-year cycle below 60 km, which suggests a conflict

between the imposed activity variation and the inherent 10-year beat period. There is no significant difference between the amplitudes of the difference fields in both cases, which is perhaps surprising considering the large differences seen at low latitudes (Figure 12).

5. Summary and Conclusion

In the modeling study presented here, we have explored a dynamical mechanism that may conspire to enhance the SCAE through the QBO. Though generated primarily by wave mean flow interaction, the amplitude and period of QBO are affected by the seasonal cycle of solar forcing. Our hypothesis is that the SCAE could result not so much from an amplitude modulation of the QBO but from a modulation of its phase and periodicity. The idea is that relatively small changes in the phase and period of the QBO, produced by solar activity, may significantly alter the wind field.

To investigate this hypothesis, we performed two modeling studies that led to different but complementary conclusions. In one we studied a hypothetical QBO with a period of 30 months, in the other one the period was close to 33 months. For both studies the model was run with and without SCRv of various amplitudes and periods. In case 1, the QBO period was stable and closely tied to the AO. In case 2, the QBO period was highly variable and therefore more susceptible to SCRv. A limited study of this kind is not suitable to draw firm conclusions. It serves however to reveal some trends and complexities involved. Further investigation across the range of possible QBO periods and SCRv forcing is required to map out more fully the details of the related SCAE phenomena.

The first case study illustrates the SCAE phenomenology associated with a QBO that has an unusually stable period. Without the ability to influence the phase of the QBO (see Figure 5), the SCRv can only modulate the amplitude of the oscillation. As a result, the net effects of the SCRv is then relatively small. Considering the magnitudes of the variations imposed on the solar heating rates, however, the resulting differences in the modulated QBO amplitude are significant. At mid-latitudes, there are no detectable signatures of the SCRv in the computed zonal wind fields. This is in spite of the fact that the AO, directly generated by solar radiation,

dominates at mid-latitudes. In summary, we conclude in this case that the SCRv can significantly modulate the amplitude of the QBO and thereby amplify the effect at low latitudes.

The second case study has in common with the first that the equatorial oscillations, and the QBO in particular, are playing a central role in generating the solar activity effect in the middle atmosphere. But the dynamical situation here is significantly different and to some extent more realistic. The QBO, having a period of about 33.5 months, is not tied as tightly to the seasonal forcing so that its phase (and period) are much more amenable to the influence from solar activity variations. As shown in Figure 11, in this case the QBO period is highly variable with or without solar activity effects. One complicating factor here is that a beat period around 10 years is generated that results from the QBO interacting with the SAO through GW filtering (Mayr et al., 2001). The beat oscillation then can be locked into by solar activity variations with the same period. This is shown in Figure 12a where the phase of the QBO gradually changes until, after about 7 years, it becomes locked in the opposite polarity (180° phase difference) to produce a large difference field. The phase of our hypothetical QBO also changes for the 8-year activity cycle (Figure 12b) but never locks into the kind of state seen in Figure 12a. In this case, the difference field clearly reveals a periodicity around 10 years to reflect the solar activity effect, and the amplitudes are close to 20 m/s at altitudes around 60 km. Eventually, in later years, the imposed phase difference becomes large enough to modify also the QBO at lower altitudes.

In contrast to Case 1 where the solar activity effect is confined to low latitudes, the effect for Case 2 extends to higher latitudes, and it is relatively large. Distinct variations are seen in the difference fields for both activity cycles (Figure 14) – but it is not clear how they are generated. One explanation might be that the meridional circulation is carrying the solar activity signature in the QBO towards higher latitudes. This has been suggested (Mayr et al., 2001) for the signature of the 10-year beat period that appears also at mid latitudes although it is generated by the QBO that is confined to low latitudes. The zonal circulation of the QBO, whose amplitude and period are modulated by solar activity, would generate such a meridional circulation through the Coriolis force. And long periods in the range of 10 years may be conducive to generate perturbations at lower altitudes where the time constant for radiative cooling is long.

The study presented here is many ways limited. The study samples are not representative of the real world, with the QBO of 30 months that is phase locked to the seasonal cycle, and the QBO of 33.5 months that is at the upper end of observed periodicities. Moreover, the 10-year

beat period associated with the second case requires that the QBO, though not stable, does not vary excessively – and this may not be assured in the real world where a great number of processes come into play that have not been considered such as variations in the GW source and ocean atmosphere interactions. Finally, we presented here a study conducted with the 2D version of our model that permits integrations over periods of a few decades. In 3D a new dimension of processes and interactions would be added to the picture that could affect the outcome significantly.

Notwithstanding these limitations, we believe that our model study does illustrate how the wave driven equatorial oscillations and the QBO in particular may affect and amplify the solar activity variations in the middle atmosphere.

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Figure Captions

Figure 1: Zonal winds at 4° latitude computed: (a) with seasonal variations of solar forcing and (b) with the same GW parameters but for perpetual equinox (taken from Mayr et al., 1998a). As seen from the spectrum (a), under the influence of seasonal forcing and with the Sun crossing the equator twice a year, a strong Semi Annual Oscillation (SAO) is generated at around 50 km that has a period of 6 months. And in this case, the QBO at lower altitudes has a period of 21 months and its amplitude is about 7 m/s. Without the seasonal cycle (b), the short period oscillation (in the place of the SAO) is 8 months and the long period oscillation in the place of the QBO of 21 months is instead only 17 months; and the amplitudes of these oscillations are much smaller.

The seasonal forcing, due to UV radiation and mainly above 30 km, thus affects not only the amplitudes of the equatorial oscillations but, significantly, it affects also their periods, and the effect extends in the QBO to lower altitudes.

Figure 2: Schematic, illustrating the adopted height variation of the relative solar activity variation in the heating rate on a logarithmic scale. For comparison, model results will also be shown for 3 times larger amplitude and with an activity cycle of 8 years.

Figure 3: Computed zonal winds at latitudes 4° (a) and 40° (b) for Case 1. The QBO in this case has a period of 30 months, and it is strongly tied to and synchronized by the SAO to produce an exceptionally stable oscillation (Mayr et al., 2000). This QBO interacts with the Annual Oscillation (AO) to generate a beat period of 5 years through GW node filtering.

Figure 4: Spectrum of the equatorial oscillations in the zonal winds at 4° north (as seen in Figure 3) obtained from a solution spanning 30 years beginning at a time the atmosphere was spun up. The spectrum is presented in terms of harmonics, h , that are related to periods by $30/h$ (years) in this case. Hemispherically symmetric (a) and asymmetric (b) components are shown, and the various “spectral lines” are identified. The 5-year beat is hemispherically asymmetric being generated by the symmetric QBO and asymmetric AO. Due to quadratic non-linear interactions (i.e., XY), in part due to GW phase filtering, the identified “side lobes” (or lobe harmonics) are generated – and they are all tied to the QBO directly or indirectly. The rich phenomenology revealed in the spectrum, and apparent in Figure 3, is thus to a large extent caused by the QBO and the wave interactions it involves.

Figure 5: Period at 4° north and at 20 km altitude obtained from the time intervals the computed zonal winds change direction. This is considered to be the period of the QBO, which dominates at this altitude. Note in this case that the variations around 30 months are very regular and thereby reveal the 5-year beat period. Also presented is the QBO period obtained from a solution with solar cycle activity variations, SCAV (illustrated in Figure 2), which does not show a discernable effect.

Figure 6: Computed differences of zonal winds at 4° north obtained by subtracting solutions with solar activity variations from a solution without solar activity. The difference field (a) is obtained by employing the standard SCAV shown in Figure 2, while for (b) the adopted SCAV is 3 times larger. In both cases, the difference fields reveal the 10-year periodicity of solar activity, but the effect is not clean but rather patchy. GW filtering apparently causes the phase reversals at altitudes above 70 km. The factor of 3 increase in solar activity does not produce a corresponding increase in the difference field, but it shows some tendency for the effect to extend to lower altitudes.

Figure 7: Spectra for a 30-year time span of the symmetric components of the difference fields in Figure 6, shown with 0.5 m/s contour intervals and the lowest contours at 1 m/s to suppress chaff. The 10-year activity cycle is evident for the nominal SCAV (a) but is significantly stronger when it is enhanced (b). This is also evident in the side-lobes at $h = 9$ and 15 that describe the modulation of the QBO, which itself is not apparent in the difference fields. Some other features in the spectrum (b) at $h = 69$ and 75 appear to be related to the 10-year modulation of the QBO that in turn can modulate the SAO (at 60). But the harmonics at $h = 5$ and 7 for (b) cannot be readily explained

Figure 8: To convey a visualization of some spectral features in Figure 7, syntheses are presented of the harmonics $h = 3, 9, 15$, which are prominent in both cases. This reveals the 10-year modulation of the QBO and for (a) it resembles also, as expected, the difference field shown in Figure 6a. For (b) the resemblance with Figure 6b is less obvious, but it does show a significant increase in the modulation amplitude commensurate with the enhanced activity.

Figure 9: For completeness, the difference fields for the zonal winds are presented at 40° latitude. These do not show any kind of sign of the 10-year activity cycle – although it is applied in the model to modulate the seasonal variations that are most pronounced in the AO at mid latitudes. Apparently, the solar activity effect is confined to low latitudes where the wave driven equatorial oscillations dominate.

Figure 10: Computed zonal winds at latitudes 4° (a) and 40° (b) for Case 2, similar to Figure 3. The hypothetical QBO in this case has a period around 33.5 months, and it interacts with the SAO to generate at both latitudes a beat period around 10 years through GW node filtering (Mayr et al., 2001).

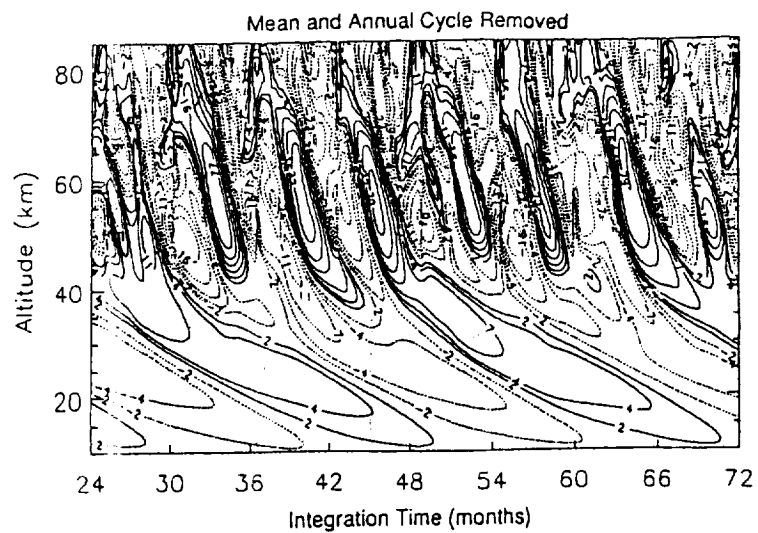
Figure 11: QBO period at 4° north and at 20 km altitude obtained for Case 2 from the time intervals the computed zonal winds change direction. Considering the 10-year beat period, for comparison, results are presented for solar activity cycles of 10 (a) and 8 (b) years. In contrast to Figure 5, large and irregular variations occur that do not reveal the beat period or any other obvious pattern. Deviating from Figure 5 also, the differences between QBO periods with and without solar activity are relatively large.

Figure 12: Computed zonal wind differences at 4° , equivalent to Figure 6, obtained for the two activity cycles. Note the large differences in (a), with contour intervals of 10 m/s, which develop after about 7 years due to a gradual shift in the phase of the QBO. Apparently, the 10-year activity cycle becomes synchronized with and phase locked to the 10-year beat period. In contrast to that, the differences for the 8-year activity cycle in (b) with contour intervals of 5 m/s are much smaller. But eventually after 25 years the phase shift produces large differences in the QBO at lower altitudes. In (b), pronounced differences are apparent, with periods near 10 years and amplitudes as large as 20 m/s, much larger than those in Figure 6.

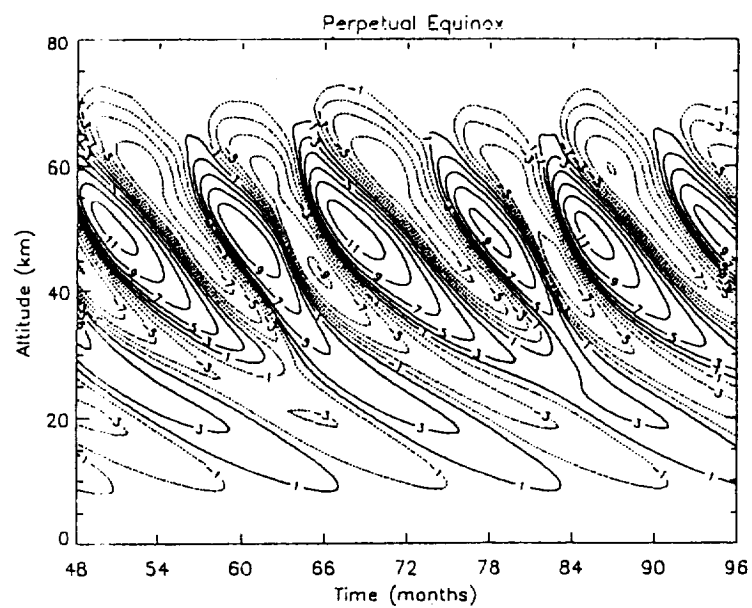
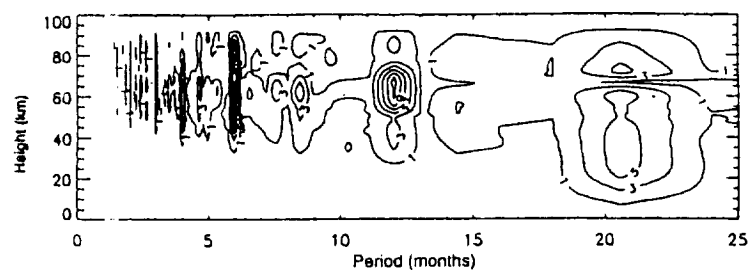
Figure 13: Spectra for 40-year time spans (10 to 50 model years) of the difference fields of Case 2, shown with 1 m/s contour intervals and the lowest contours at 3 m/s to suppress chaff. The periods are now related to the harmonics, h , by $40/h$ (years). Commensurate with Figure 12, the QBO feature dominates in (a), but the AO and SAO (firmly tied to the seasonal forcing) are eliminated by differencing. The 10-year activity cycle and its second harmonic are pronounced and appear in the side-lobes of the AO and SAO. Also shown, though fussy, are the corresponding side-lobes for the QBO. The pronounced features at $h = 66$ and 94 describe the modulation of the SAO by the QBO, and the ones at $h = 62$ and 98 in turn are associated with the modulation of the QBO by the activity cycle. Similar features are evident for the 8-year cycle in (b), except that the QBO signature is much weaker. In addition to the harmonic at $h = 4$ for the

10-year periodicity, a pronounced one occurs also at $h = 6$ that corresponds to a period of about 6.7 years, indicating a shift towards the 8-year activity cycle.

Figure 14: Difference fields at 40° latitude for the 10- and 8-year activity cycles. In contrast to Figure 9, there is an effect in this case and it is large. Periodicities around 10 years are seen in the wind fields, and the amplitudes are on the order of 10 m/s in both cases.



a



b

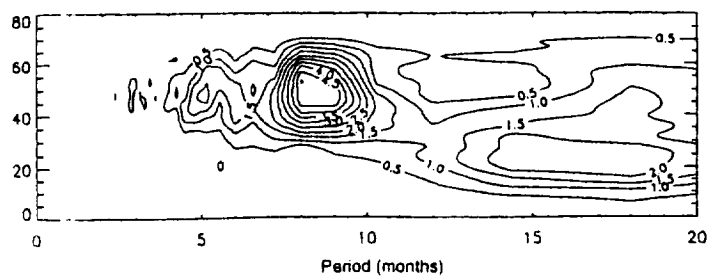


Figure 1

Relative Solar Activity Variation of Radiation (SAVR)

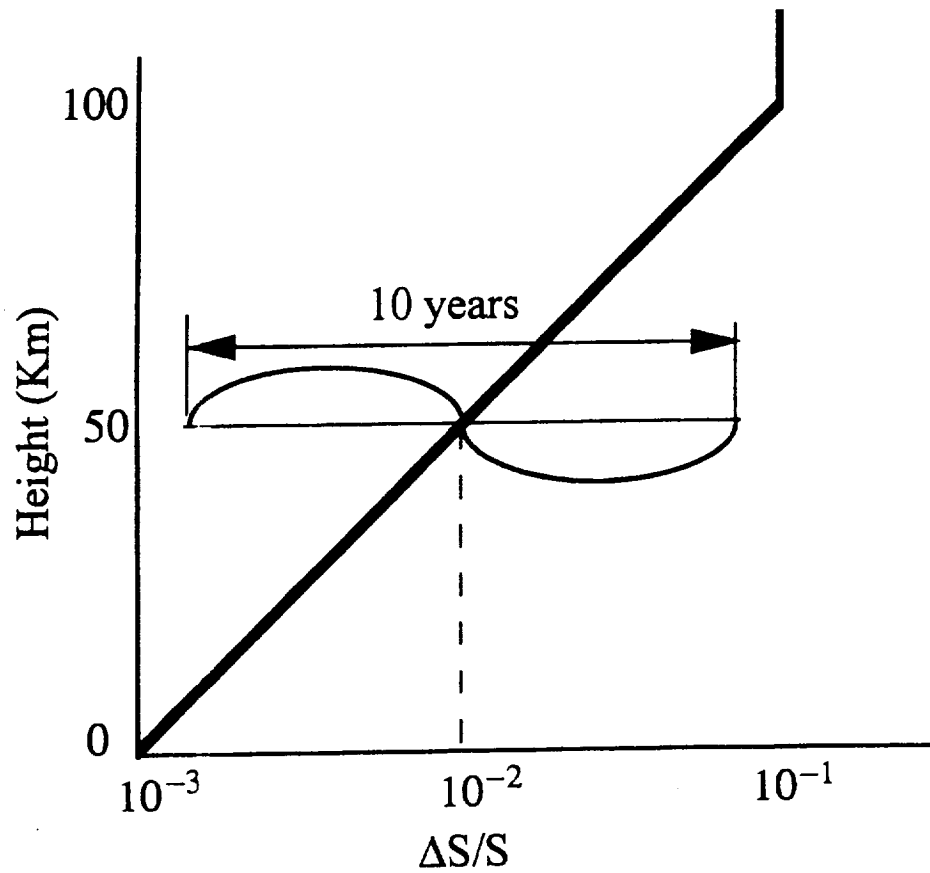


Figure 2

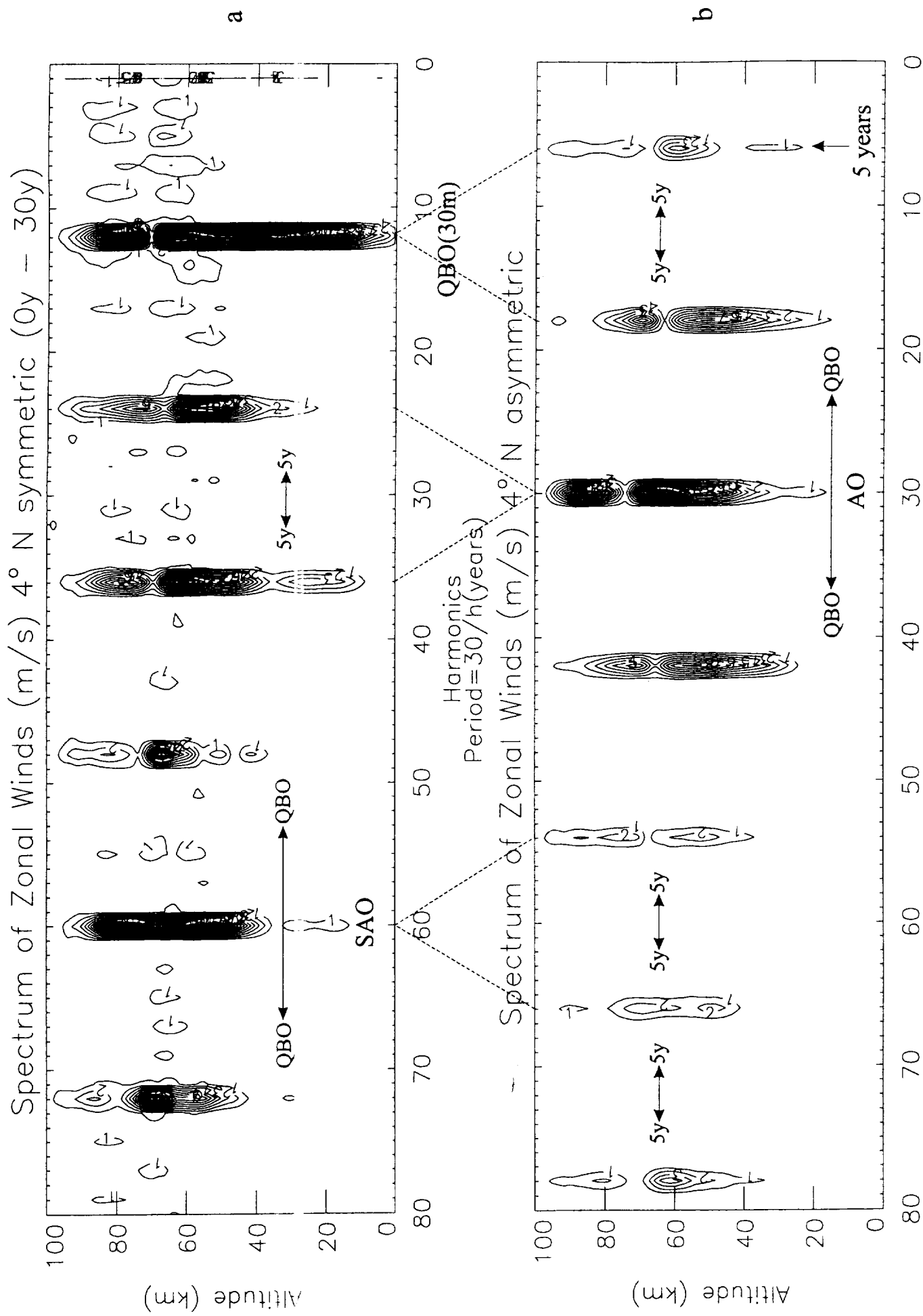


Figure 4

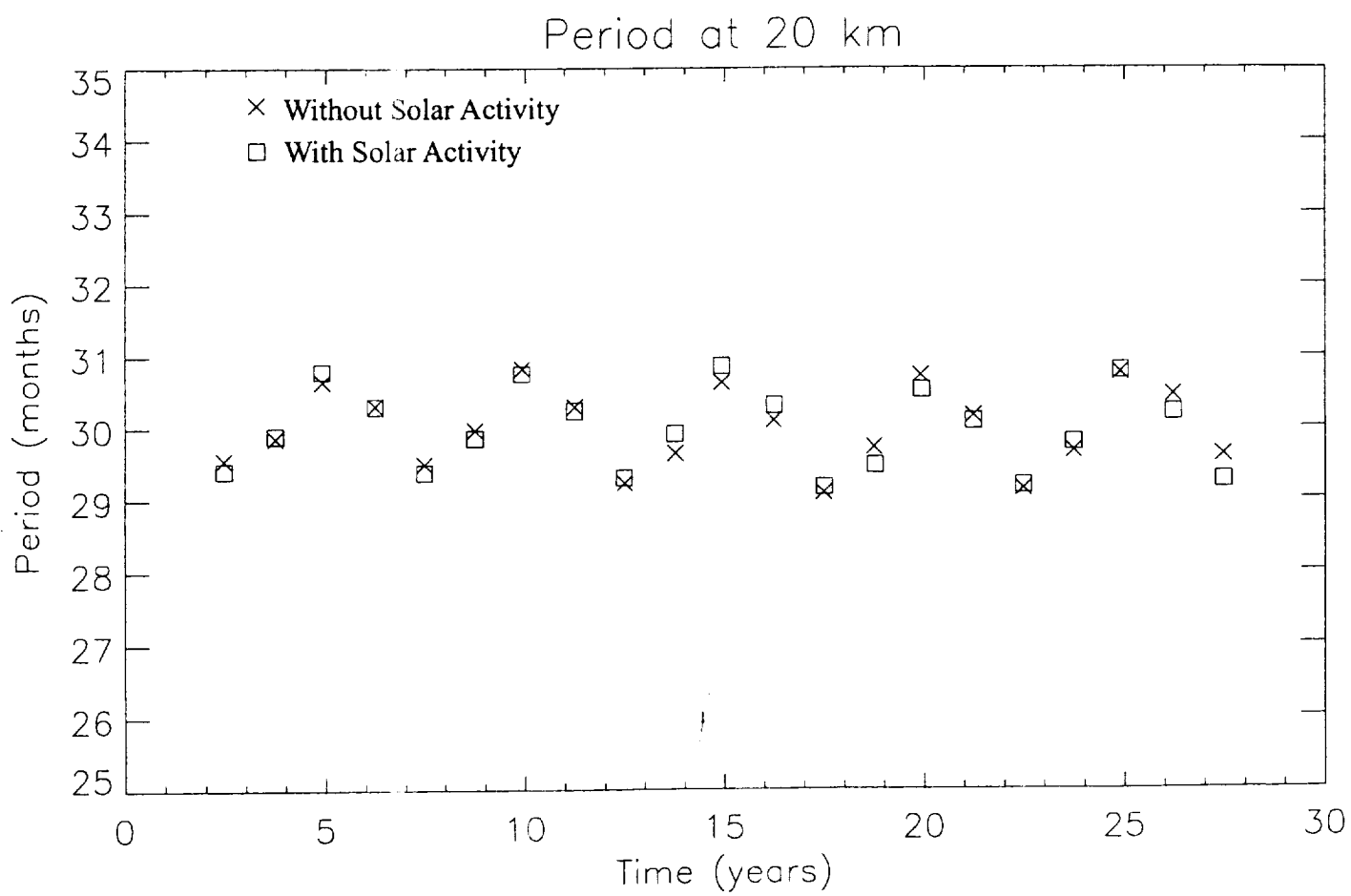


Figure 5

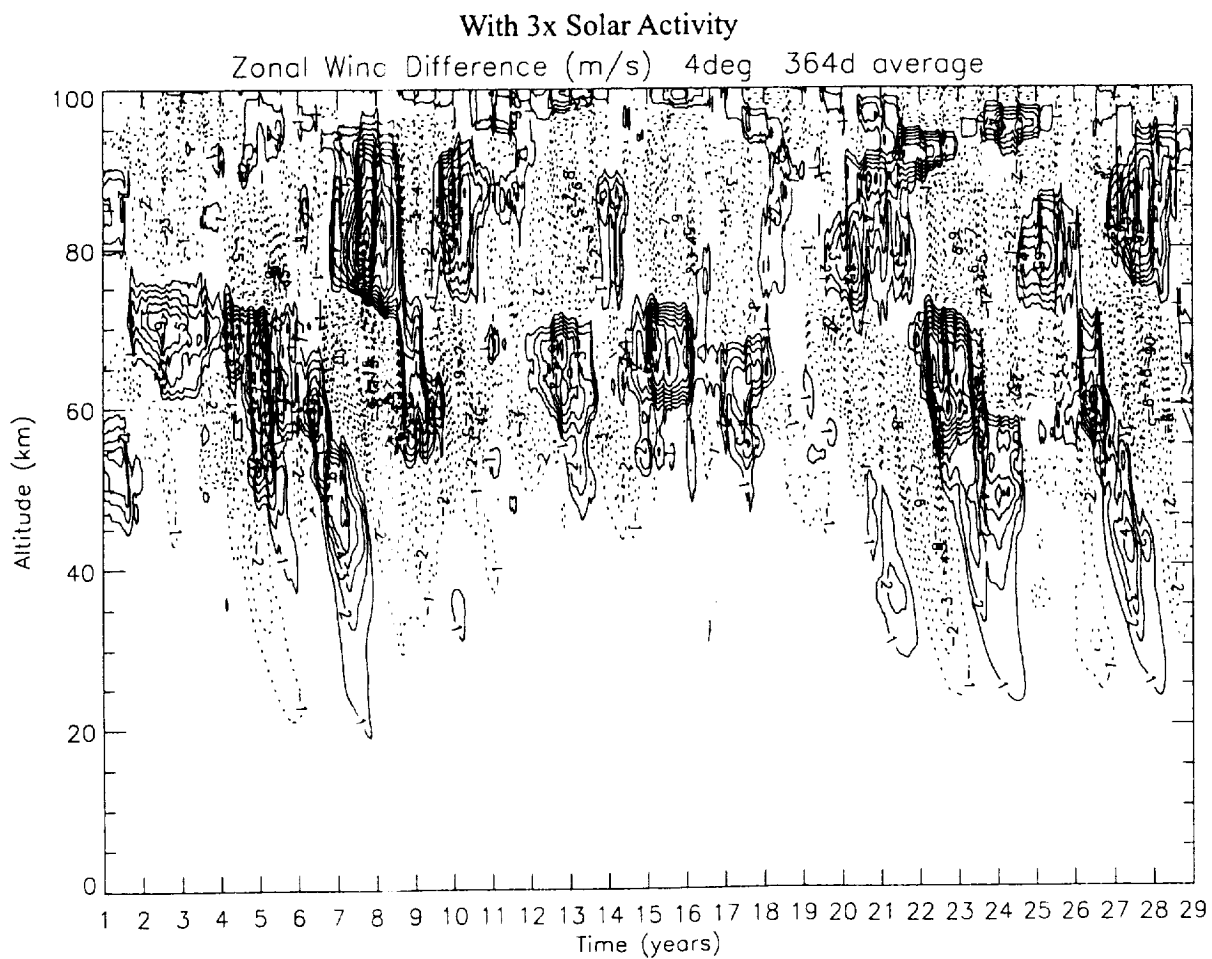
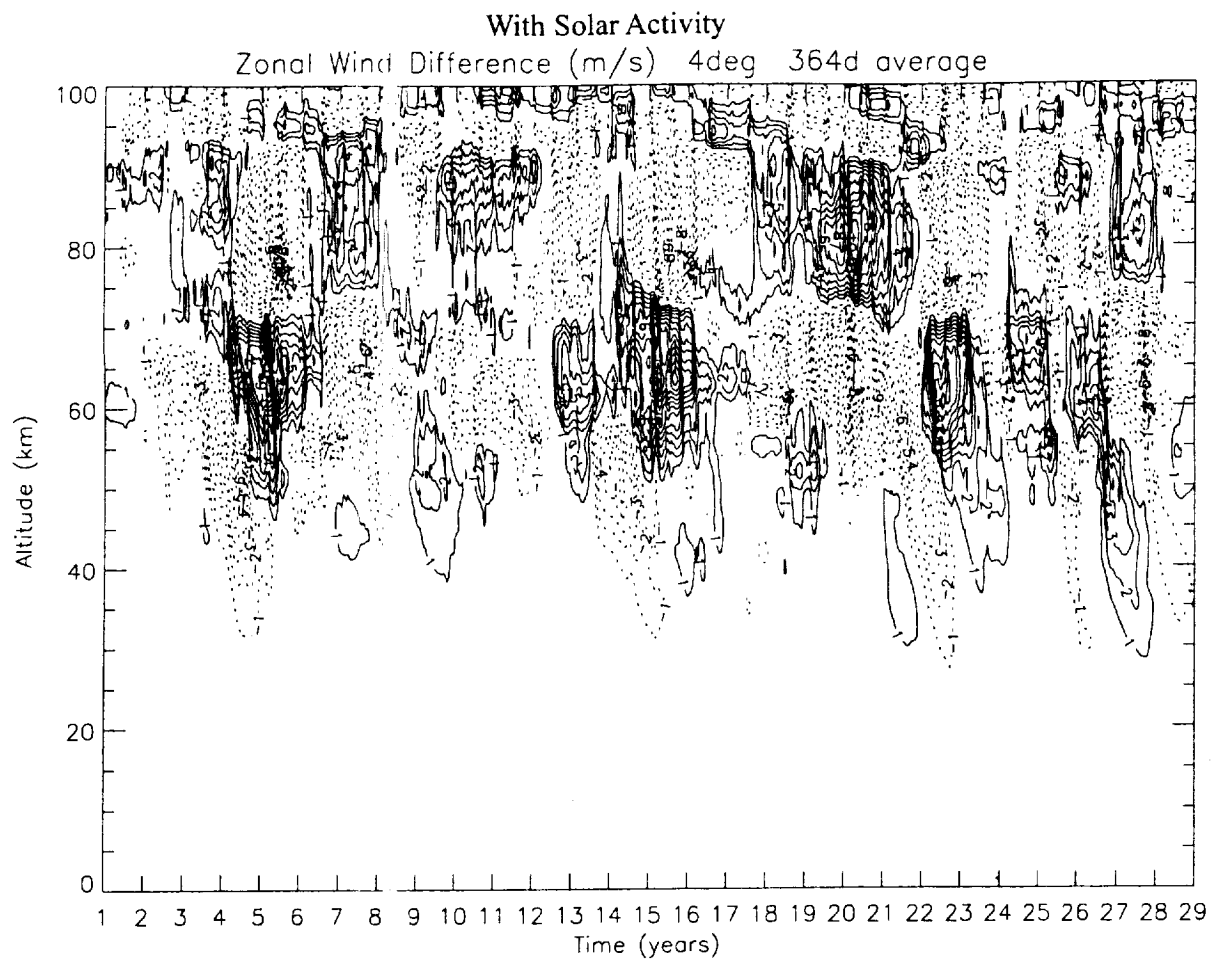
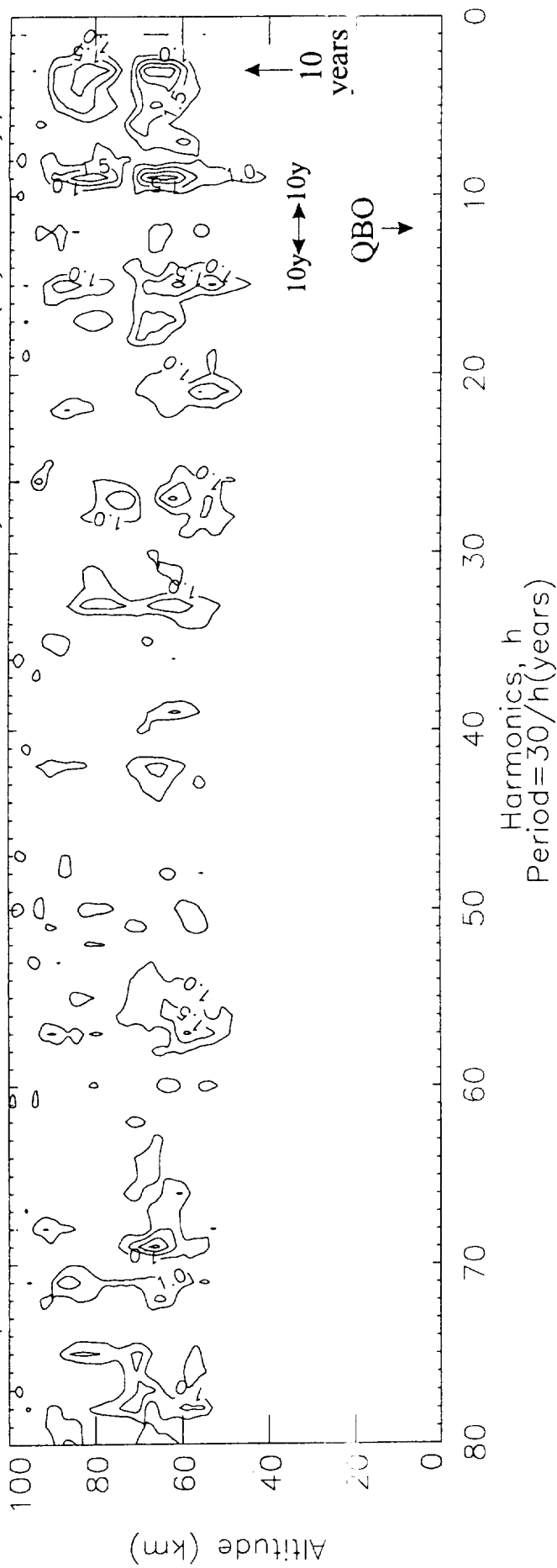


Figure 6

With Solar Activity

Spectrum of Zonal Wind Difference, 4° N symmetric, (0y - 30y)



With 3x Solar Activity

Spectrum of Zonal Wind Difference, 4° N symmetric, (0y - 30y)

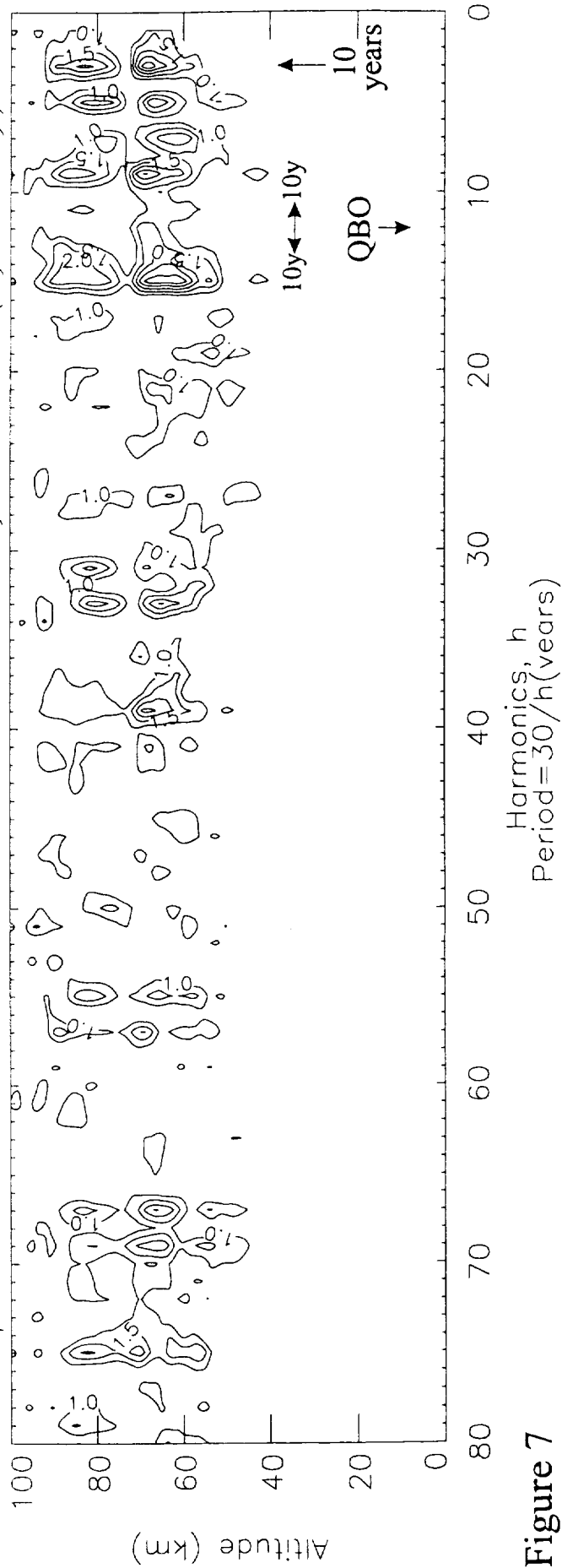


Figure 7

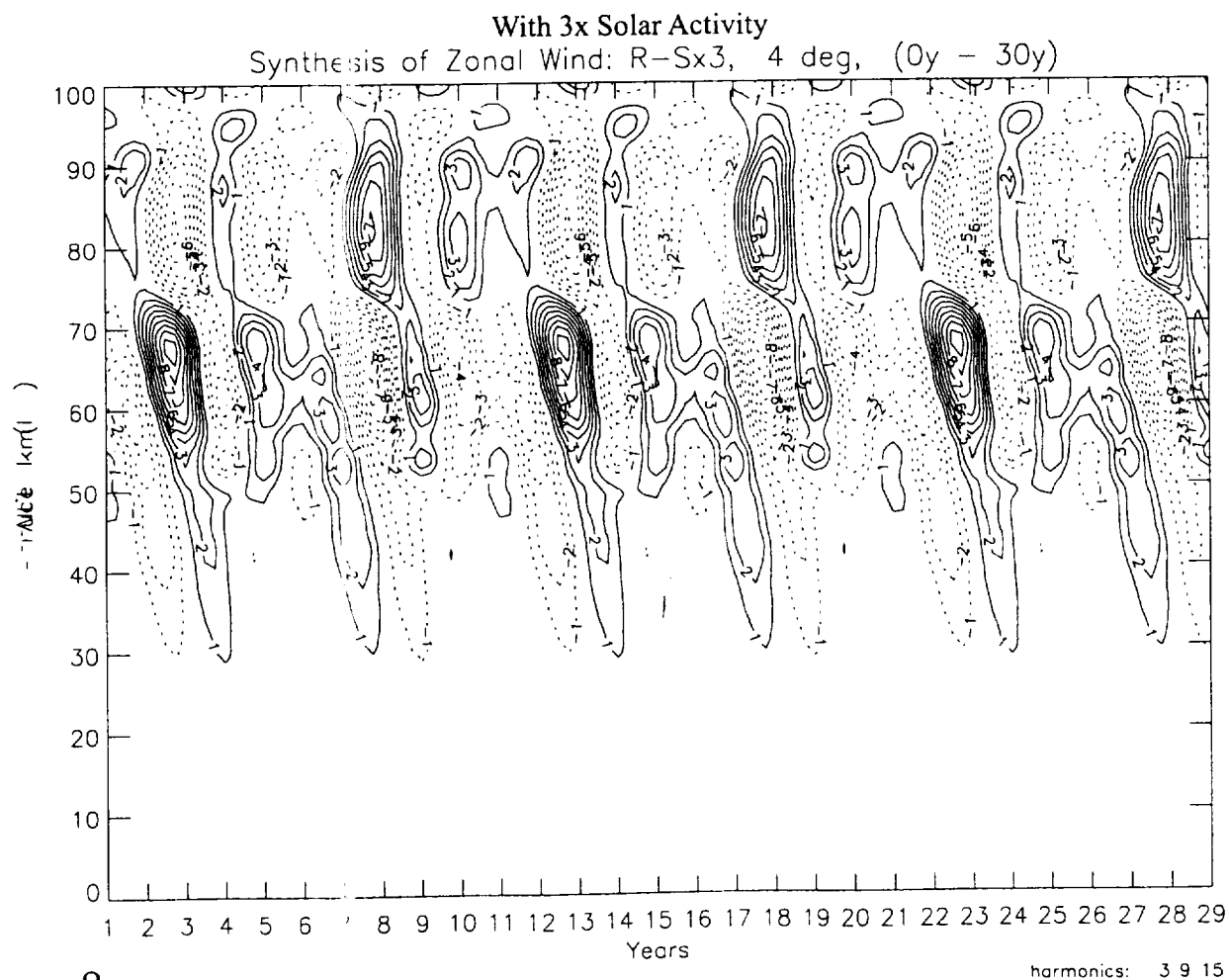
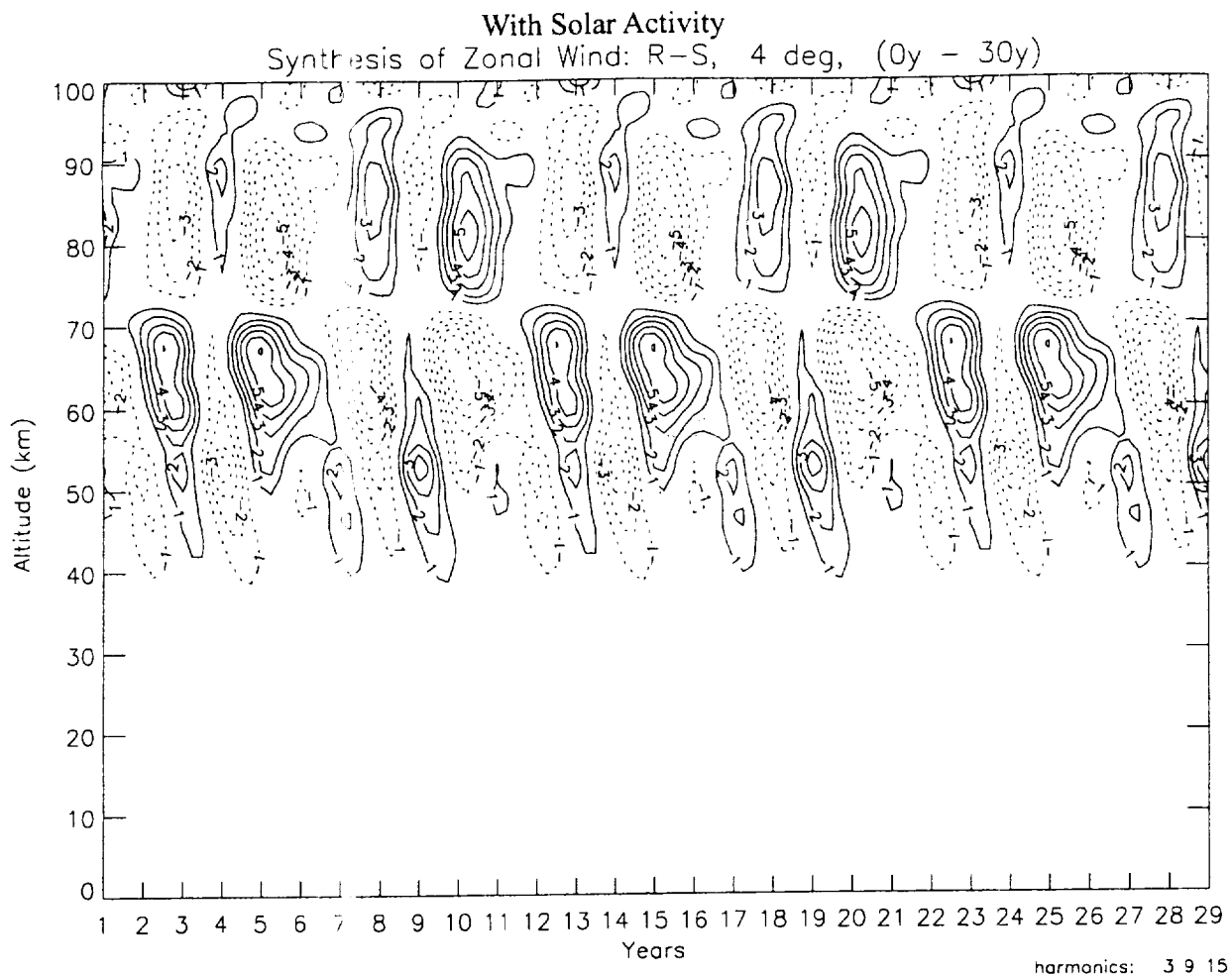


Figure 8

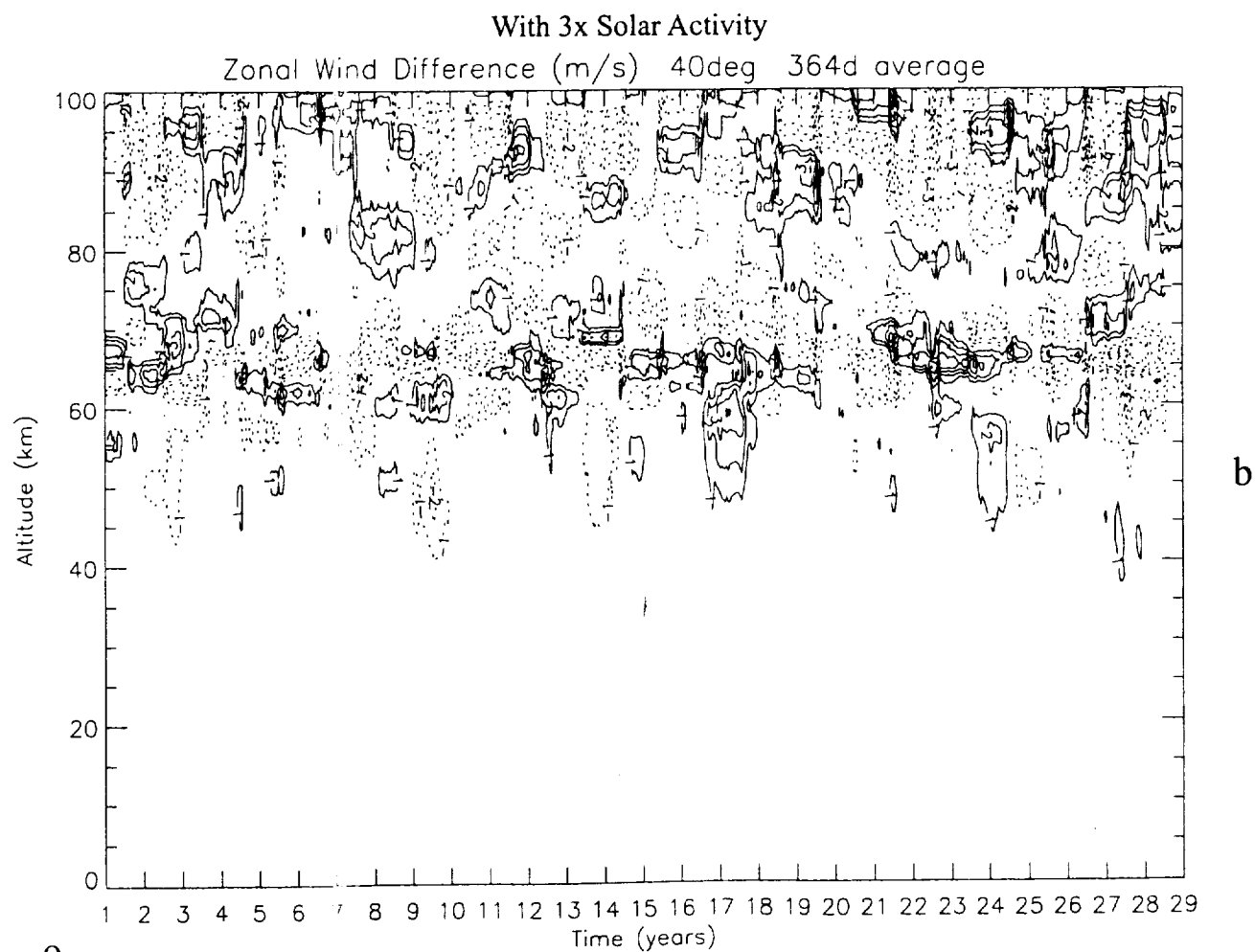
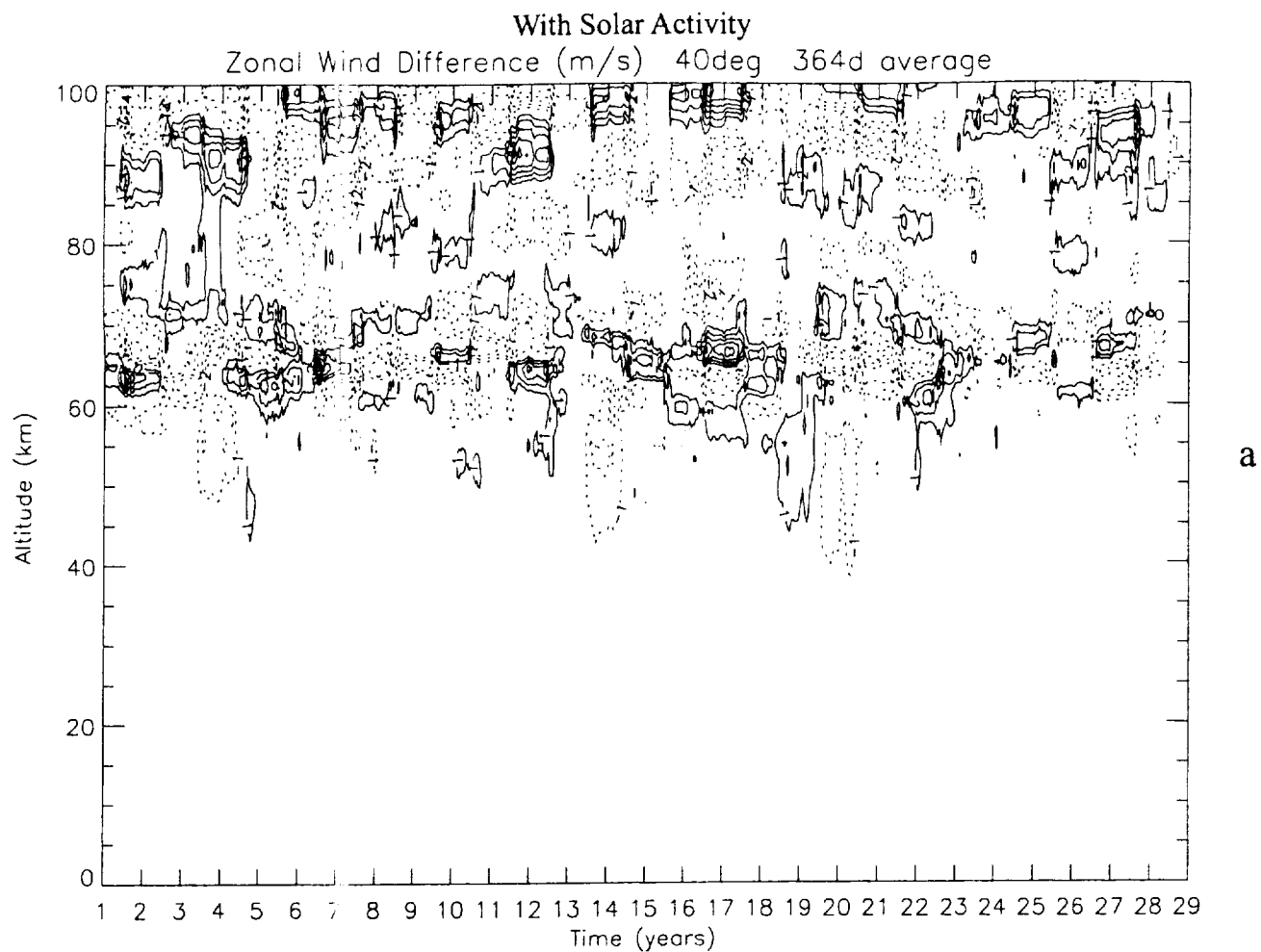


Figure 9

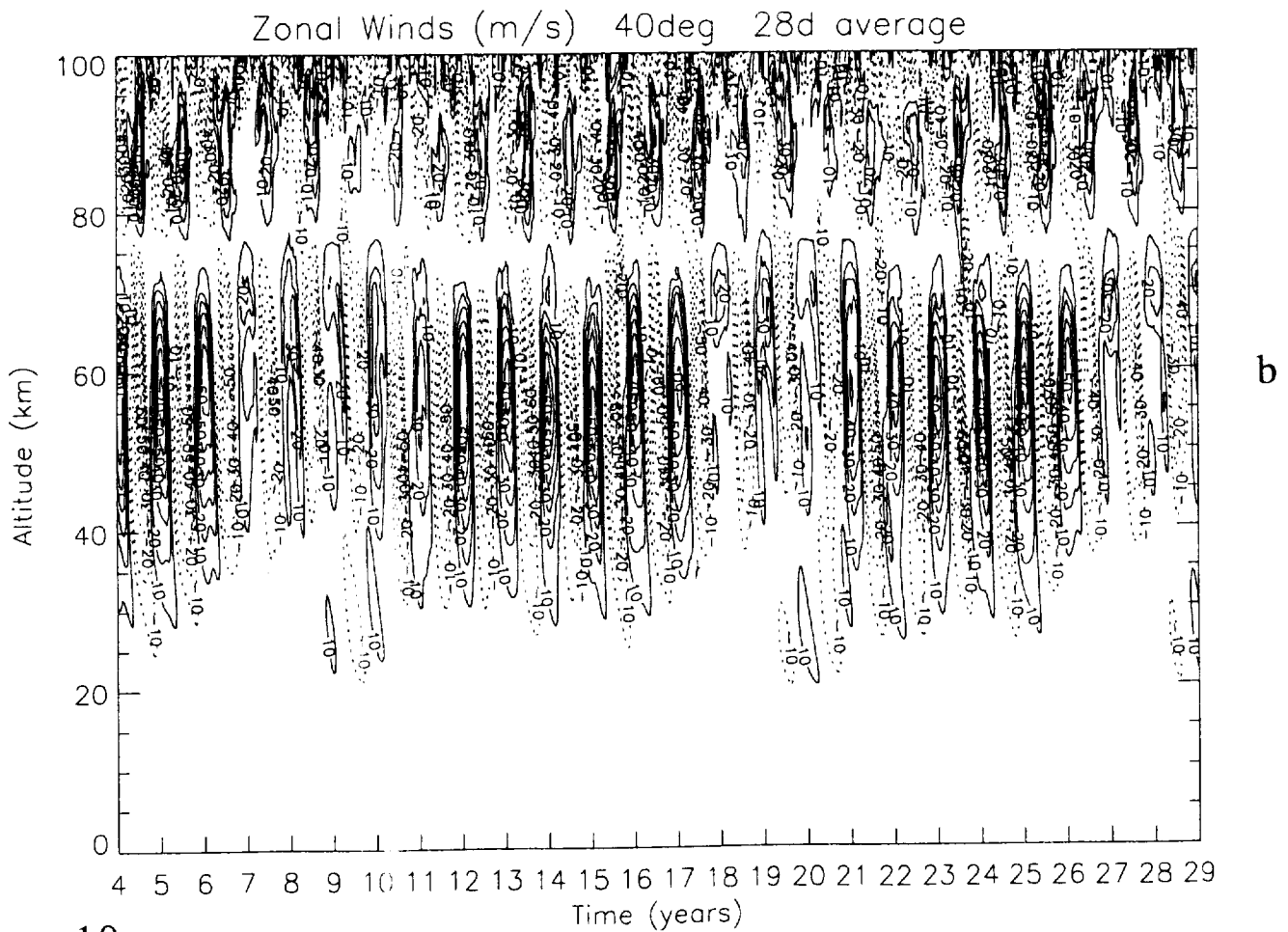
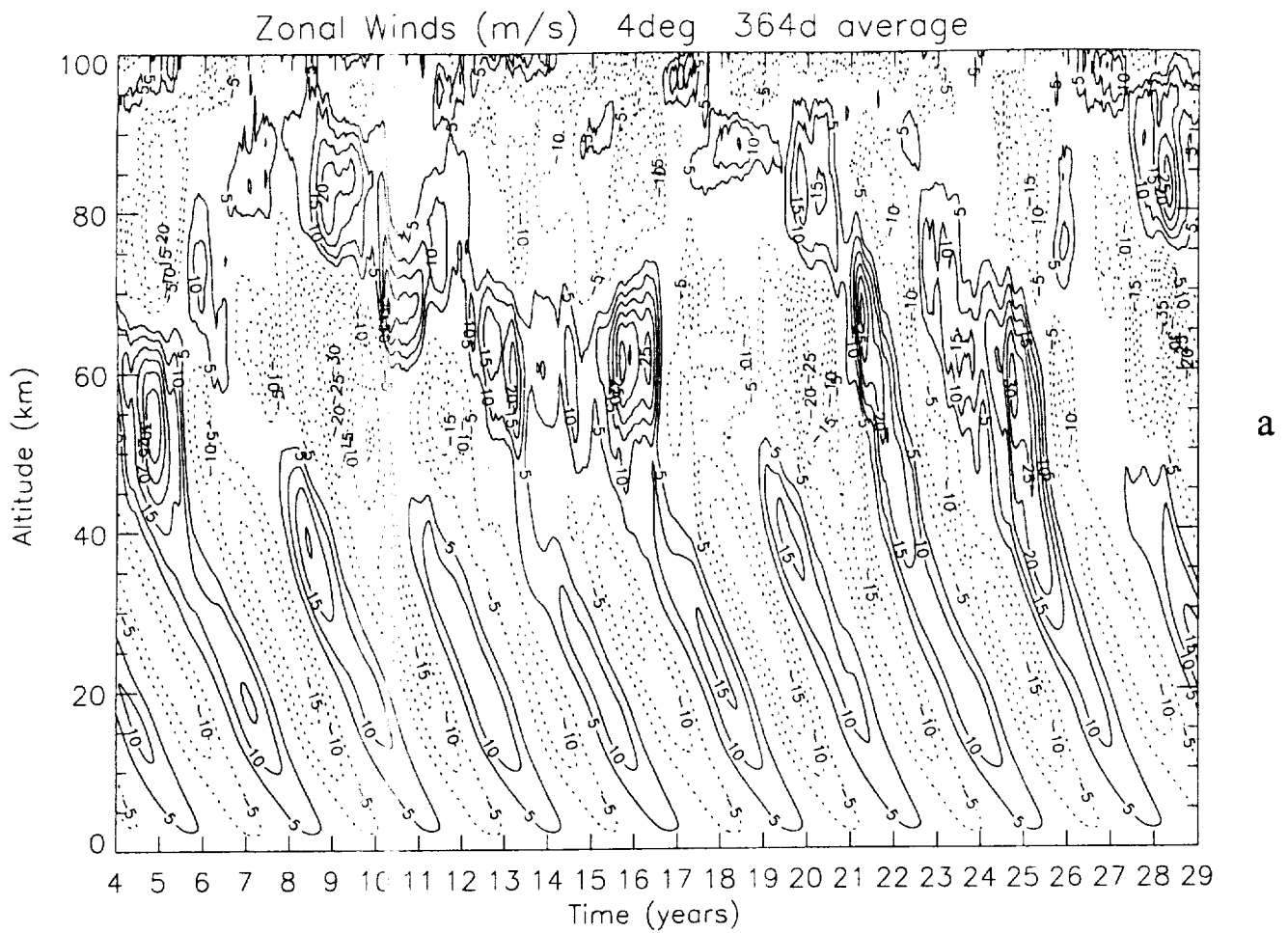


Figure 10

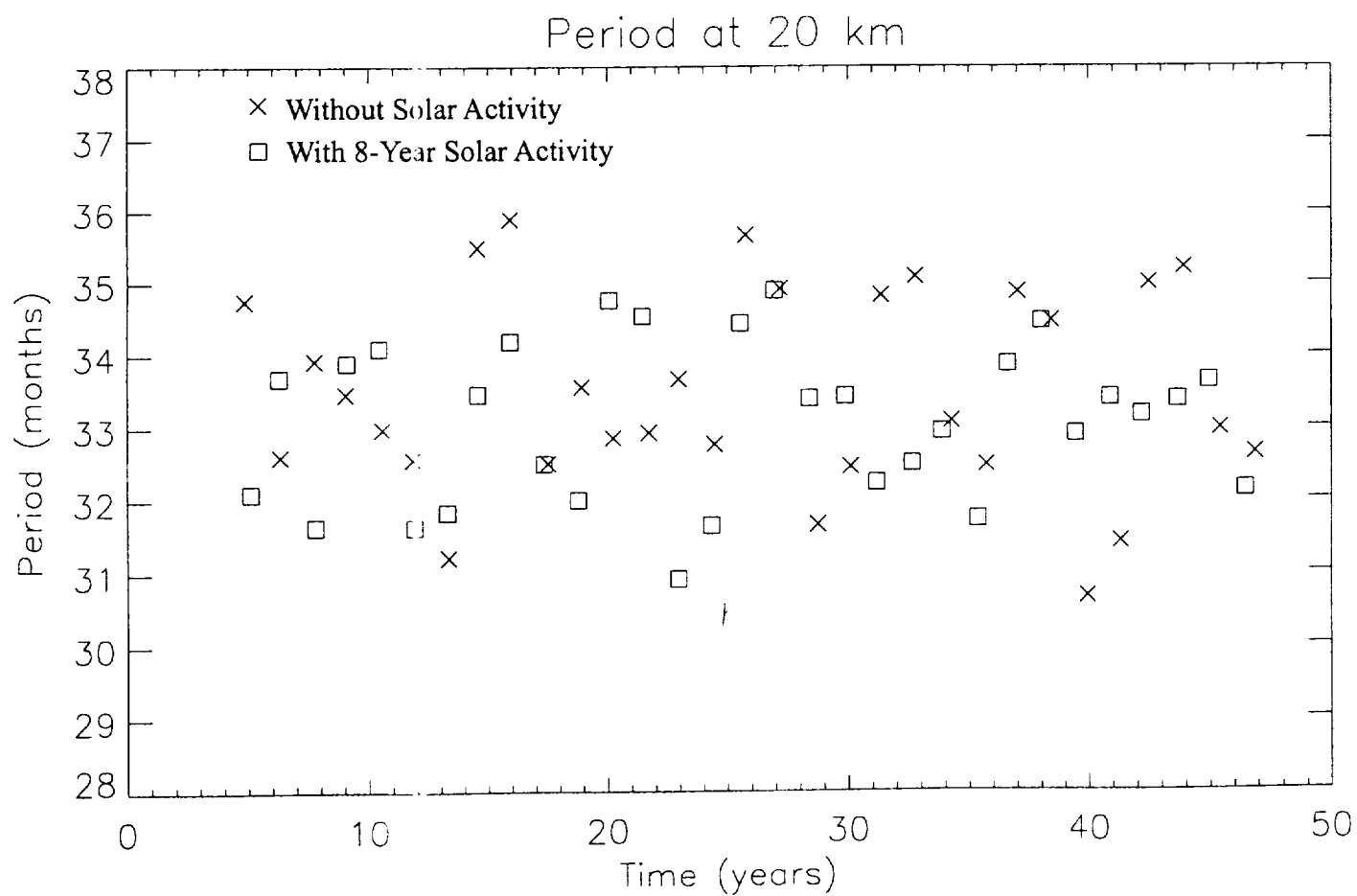
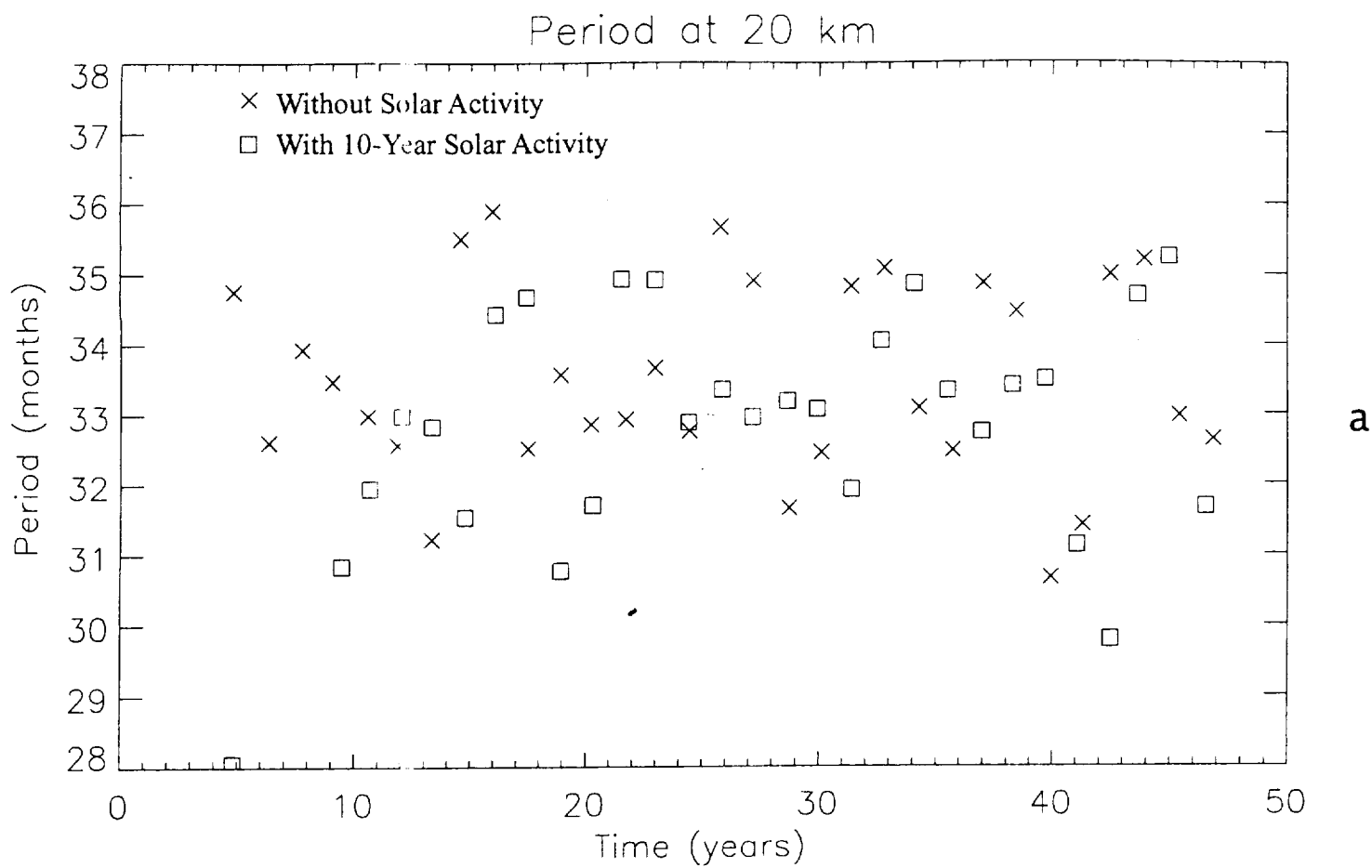


Figure 11

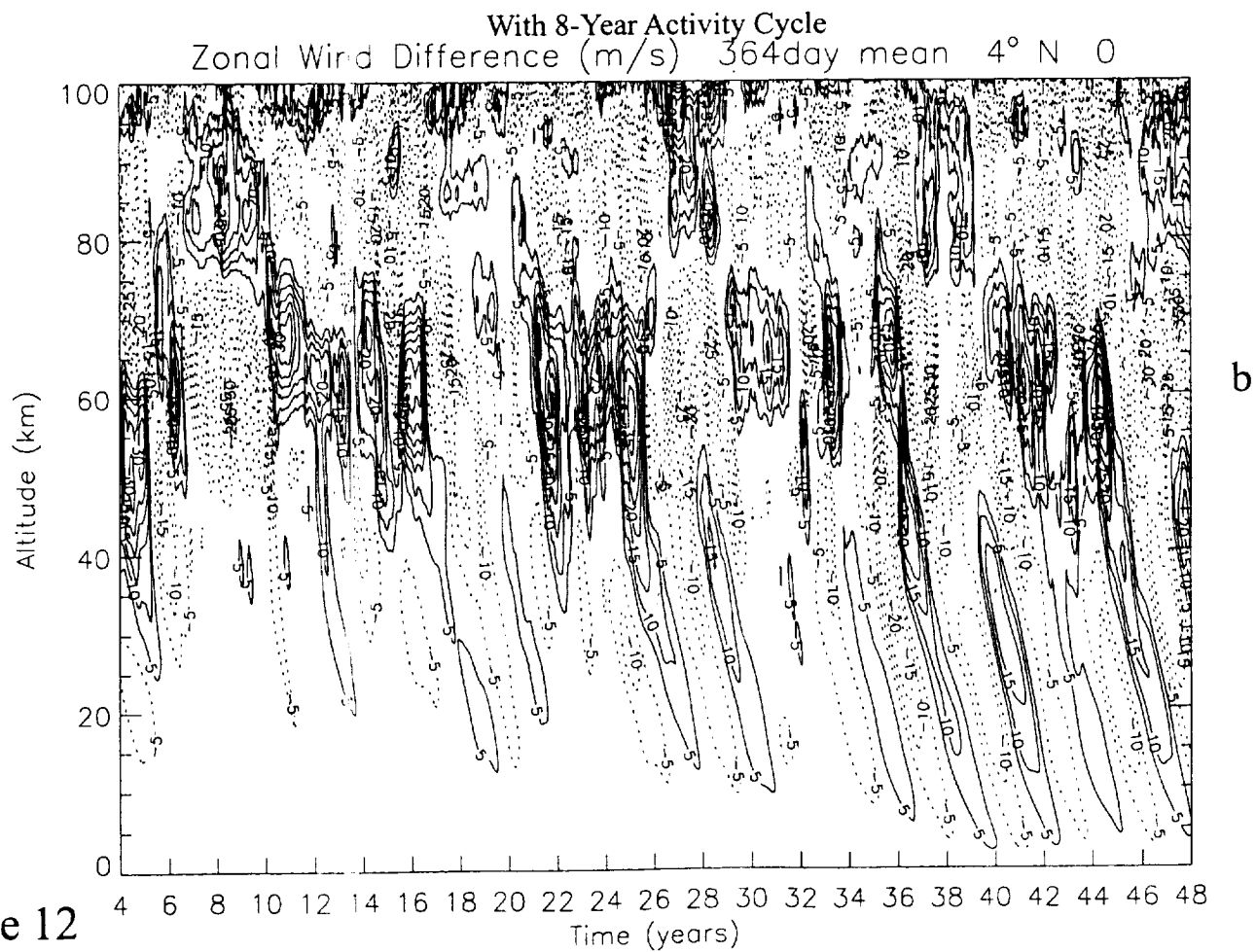
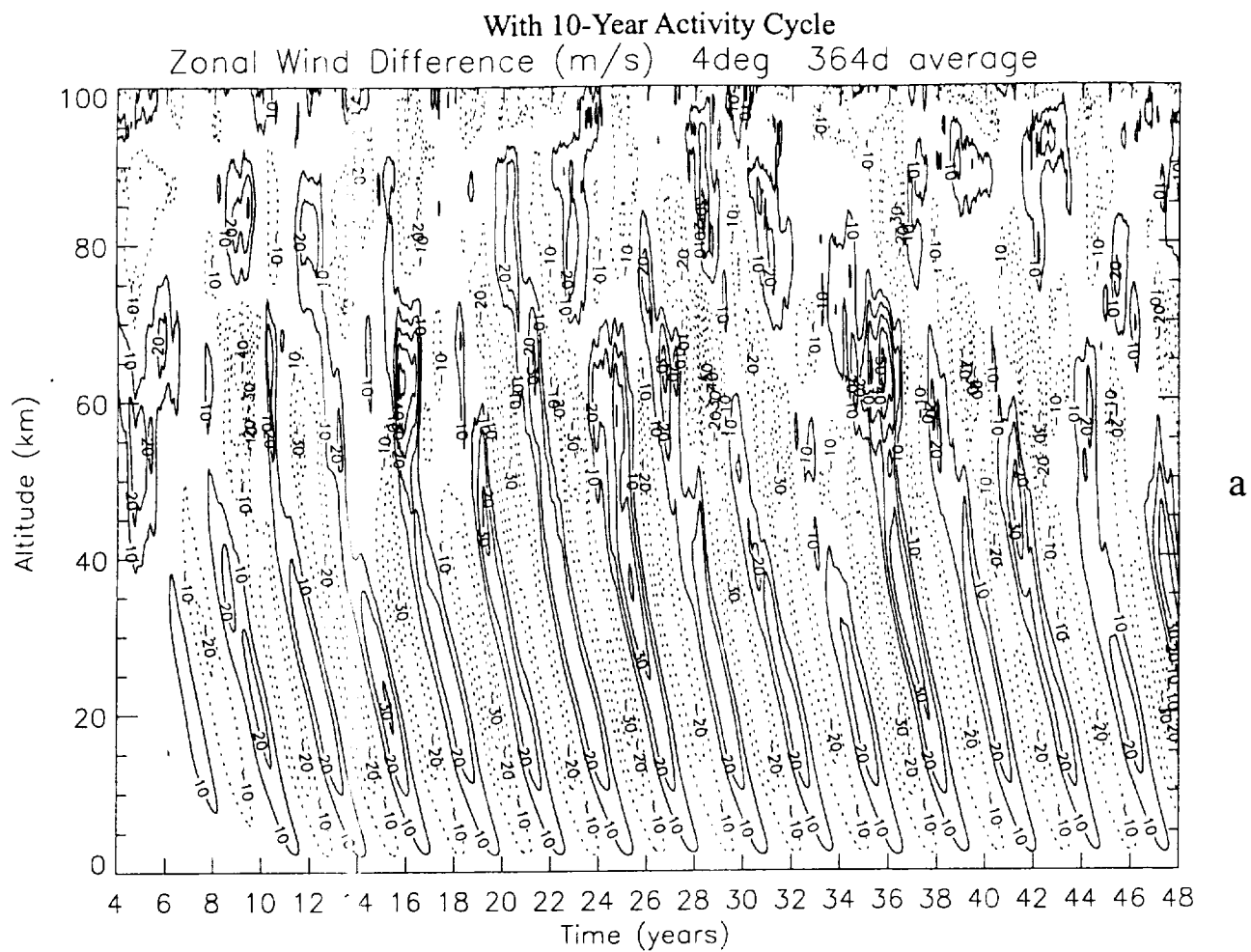


Figure 12

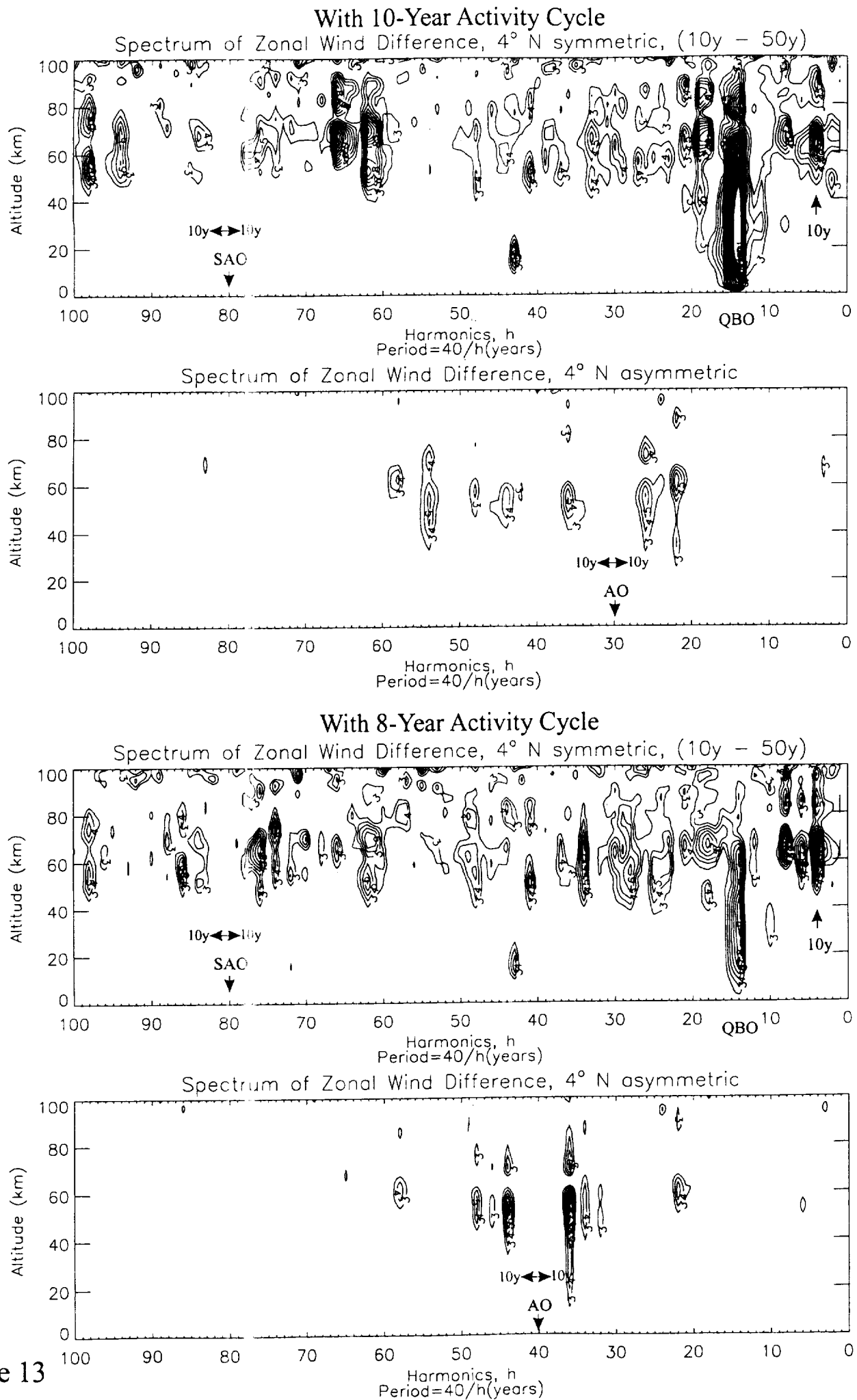
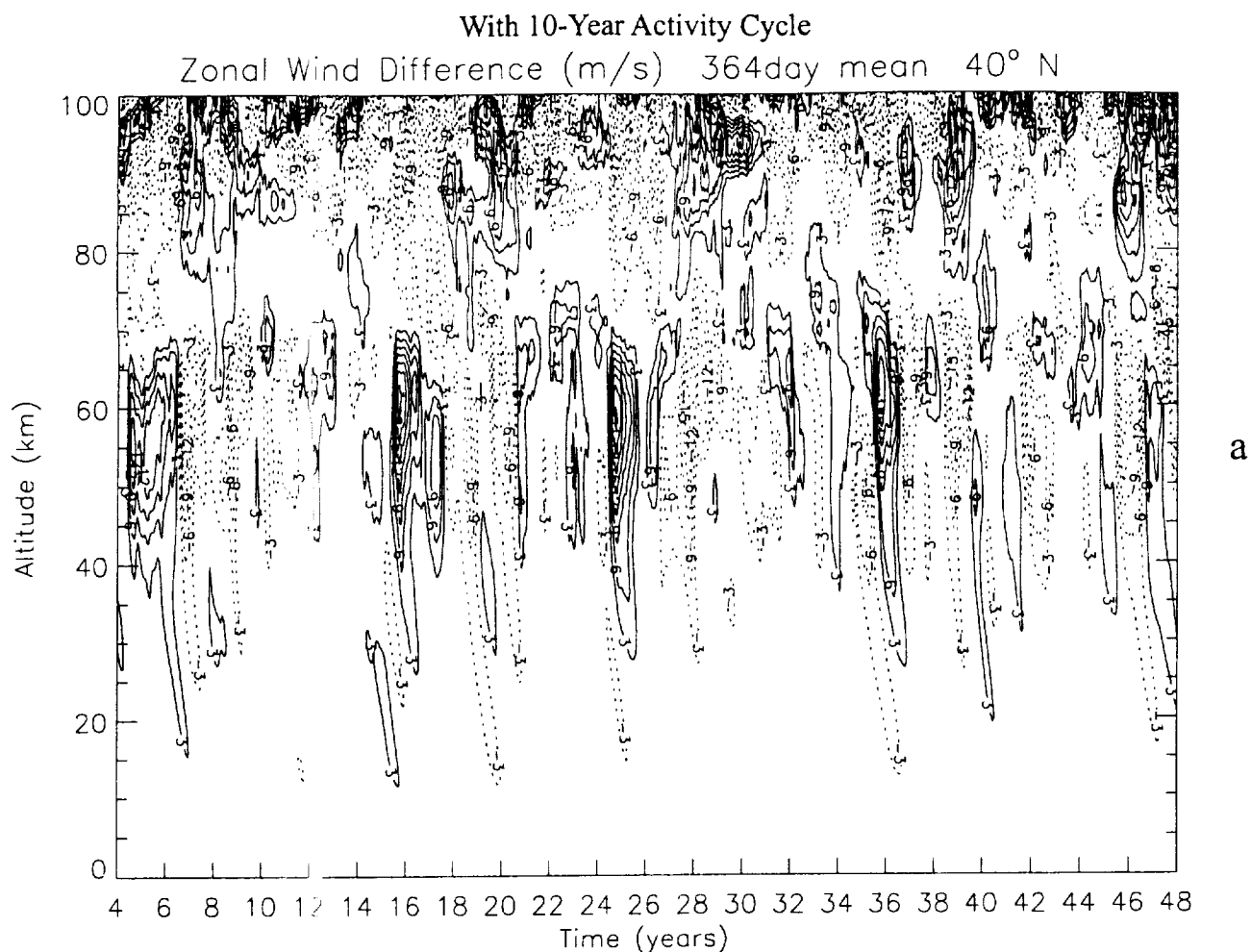


Figure 13



Popular Summary

Solar Cycle Variations and Equatorial Oscillations: Modeling Study

Solar activity effects in the lower and middle atmosphere are difficult to explain on the basis of the small changes in solar radiation that accompany the 11-year cycle. It is therefore reasonable to speculate that dynamical processes may come into play to produce a leverage. A natural candidate for such a leverage is the Quasi Biennial Oscillation (QBO) in the zonal circulation at low latitudes, which is driven primarily by wave mean flow interaction. This oscillation is also strongly influenced by the seasonal cycle in the solar radiation, and this influence extends to low altitudes referred to as “downward control”. We integrated a 2D version of our Numerical Spectral Model to cover several decades with solar cycle variations of the heating rates, which changed on a logarithmic scale from 0.1% at the surface to 1% at 50 km to 10% at 100 km. Our numerical experiments indicate that, under certain conditions, the small solar flux variations can change the QBO period (and phase), and this in turn can produce relatively large variations in the wind field.

H. G. Mayr, J. G. Mengel, D. P. Drob, K. L. Chan, and H. S. Porter